Thermal Design Aspects of the PowerSphere Concept

By

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Background

The Aerospace Corporation has independently developed conceptual designs for microsatellites and nanosatellites. This development of microsatellites and nanosatellites for low earth orbits requires the collection of sufficient power for onboard instruments with a low weight, low volume spacecraft. Because the overall surface area of a microsatellite or nanosatellite is small, body-mounted solar cells are incapable of providing enough power. Deployment of traditional, rigid, solar arrays necessitates larger satellite volumes and weights, and also requires extra apparatus needed for pointing. One potential solution to this "power choke" problem is the deployment of an appropriately sized, lightweight, spherical, deployable power system. This power system, termed the "PowerSphere", would offer a

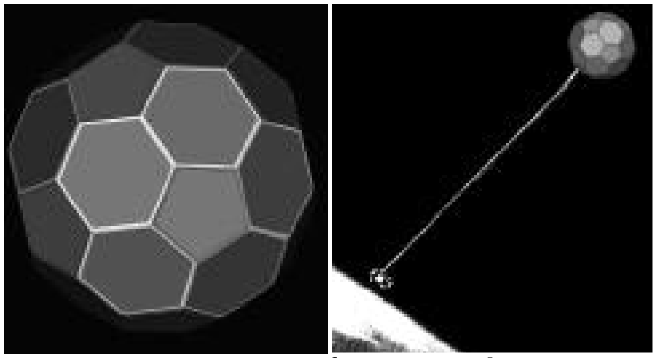

Figure 1. Artist Concept for PowerSphere

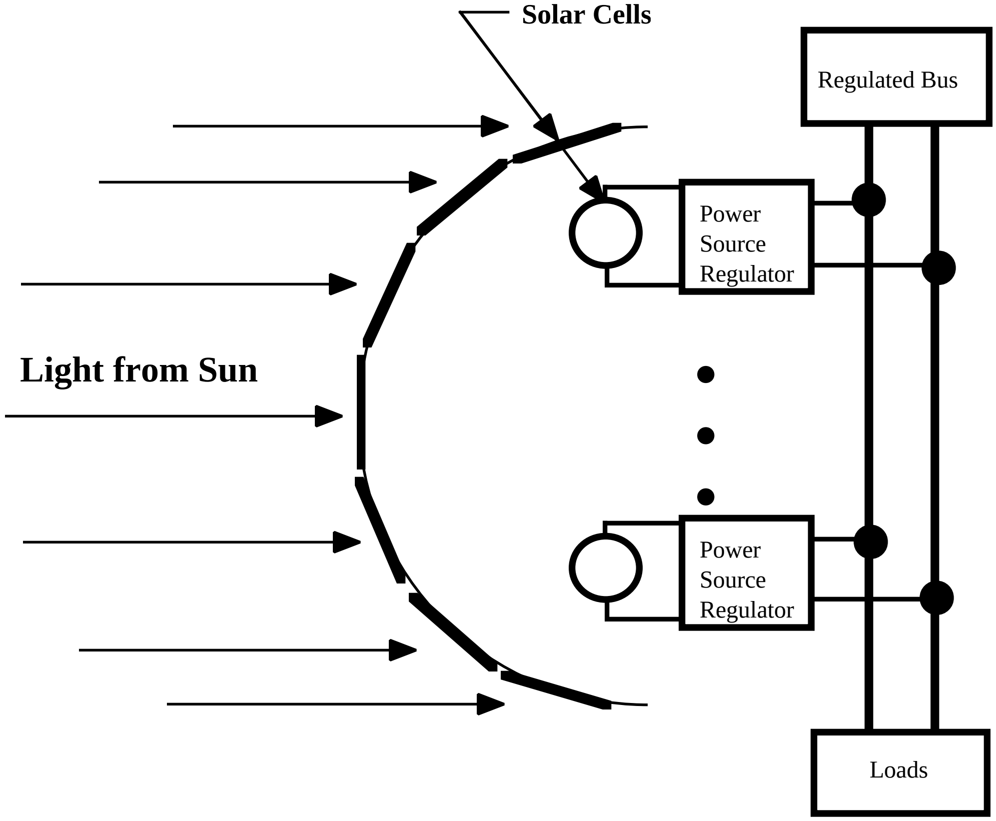

Figure 2. Solar Cell Connection Scheme for PowerSphere

	Spinner	*3-Axis w/ Deployable*	*Power Sphere*
Solar Array Weight	*240g*	*300g*	*350g*
Array Tracking & Pointing	*0g*	*500g*	*0g*
Battery Weight Li-Ion Technology	*140g*	*140g*	*140g*
PMAD Components	*200g*	*200g*	*200g*
Total System Weight	*580g*	*1140g*	*690g*

Table 1. Weight Trade Summary for the Various Power System Architectures Proposed for Powering Micro and Nano Satellites

high collection area, low weight, and low stowage volume, and eliminate the need for a pointing mechanism. Figure 1 is an artist's depiction of a PowerSphere.

The PowerSphere concept was compared to conventional satellite power system configurations. Configurations considered were a spinner and three-axis stabilized with sun tracking by a deployable array. The results of the evaluation of these concepts showed that the spinning configuration would have power output limitations which could severely limit payload capabilities and types. The high weight penalty for sun tracking and array pointing for the three-axis configuration would increase the total weight of the micro or nano satellite to unacceptable levels for most missions considered for these types of satellites. Cost was another factor in ultimately rejecting conventional power system configurations and the development of the PowerSphere concept.

The PowerSphere concept solved the power limitation of the spinner by providing a lightweight deployable solar array using thin-film solar cells and an inflatable/deployable support structure. The spherical shape of the array eliminates any need for sun tracking and array pointing. Tables 1 and 2 provide a summary of the trade study performed for each of the three power configurations explored in developing the system architecture for the PowerSphere.

The Aerospace-funded PowerSphere concept development included five different investigation thrusts. These included the development of the top level system architecture, thermal analysis for operation in the space environment, thermal cycle testing of candidate thin film solar cells, development of the Power Management and Distribution (PMAD) system for the Power Sphere (Figure 2 depicts the PMAD architecture for the PowerSphere), and the development of laboratory diagnostic techniques to detect structural and chemical changes in a thin-film solar cell being developed for the terrestrial market.

The technical focus of this paper will report on the work done on the design of the thermal control system for the PowerSphere. The thermal response of the thin film solar cell material is critical for maintaining the temperature of all components within acceptable ranges.

	Spinner	*3-Axis w/ Deployable*	*Power Sphere*
Requires Attitude Control	*No*	*Yes*	*No*
Limited Power for Microsat Load	*Yes*	*No*	*No*
High Power to Mass Ratio	*Yes*	*No*	*Yes*
Potential for Automated Mass Production	*No*	*No*	*Yes*
Mass Comparison	*Low*	*High*	*Low*
Cost	*High*	*High*	*Low*

Table 2. Comparison of Attributes of the Various Power System Architectures Proposed for Powering Micro and Nano Satellites

Thermal design requirements

The desired actual operating temperature of the thin film silicon solar array material is around 80°C, with a maximum of 100°C and no specified lower limit. Given the historical uncertainties observed in the thermal analysis of space vehicles, a margin of 10°C will be applied to all predicted temperatures. Thus the maximum predicted temperature allowed for the solar cells would be 90°C which would allow for a 10°C margin to guarantee that the 100°C upper limit is not exceeded.

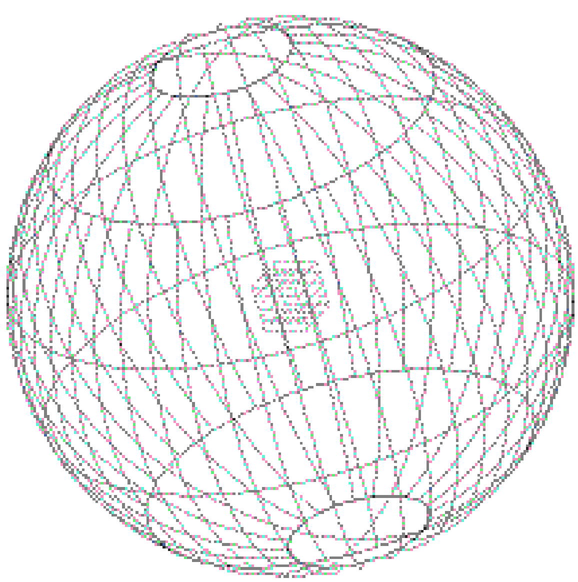

Figure 3 - PowerSphere Geometric Math Model

For the PMAD components, it was assumed that the electronics would be compatible with the generic MIL STD 1540 acceptance temperature range of -24 to +61°C. Thus, the upper and lower limits prediction range for the electronics are -14 to +51°C.

The battery will be kept within a 0 to 30°C range to maintain long life. This gives a very narrow allowable range of 10 to 20°C for predicted battery temperature. This narrow allowable temperature range can complicate the thermal design requiring active thermal control elements.

The solar absorptance and IR emittance of both sides of the baseline solar array film were measured. The cell side has an absorptance of 0.82 and an emittance of 0.39 while the backside (non-cell side) also has an emittance of 0.39.

Powersphere thermal analysis

Analytical model

For the purposes of this analysis, it was assumed that the PMAD components are mounted in a small package located at the center of the spherical solar array. The thermal model consisted of a single node for the PMAD package and 50 nodes for the solar array, as shown in Figure 3. The array was modeled with 50 nodes so that temperature gradients around the sphere could be calculated.

Predicted solar array flight temperatures

The low emittances on both sides of the solar array film would cause the sun-facing side of the solar array to run quite hot, given its high solar absorptance. In order to get the temperatures down to reasonable levels, it was assumed that the inside (non-cell) side of the material could be painted black, or otherwise coated, to give a strong radiative coupling across the inside of the sphere. Flight temperatures of the solar array were then predicted for the β=90° (no eclipse) orbit as a function of the surface emittance of the exterior (cell) side of the array. The results, shown in Figure 4, indicate that a cell-side surface emittance of around 0.80 is needed to keep the hottest areas of the array below 80°C with no power being drawn out of the thin film solar cells.

Temperatures were then predicted for the β = 0°, maximum eclipse orbit. The solar cell temperatures were found to cycle from 86 to -117°C assuming a cell-side surface emittance of 0.80. It was also noted that there will be a large temperature gradient (typically on the order of 100°C) from the sun-side to the backside of the sphere whenever it is in the sun.

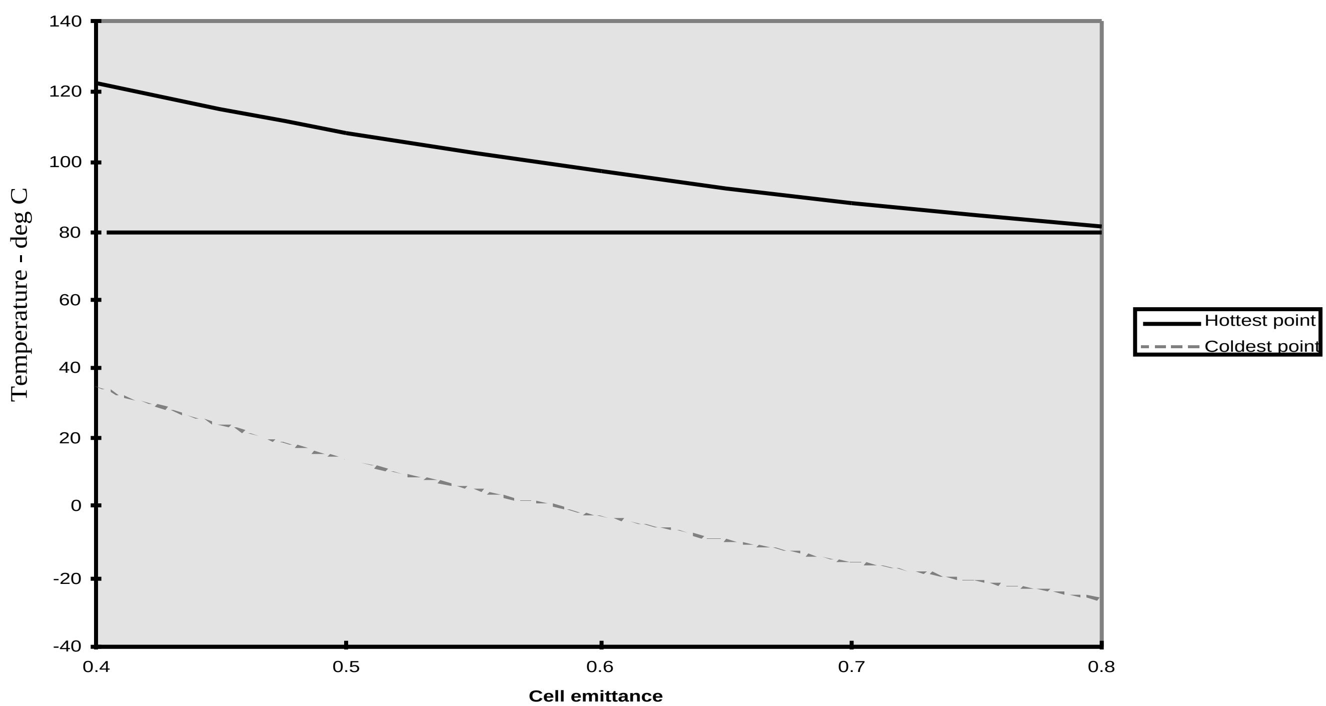

Figure 4 - Solar Cell Temperatures in β = 90° Orbit

Coating	Emittance
Tefzel on ZO^2 coated cell (unbonded) :	.69
Tefzel on bare cell (unbonded) :	.65
Teflon coated cell	.69

Table 3 - Coatings to Raise Front-Side (solar cell) Emittance

Investigation of Thermal Properties of Thin Film Solar Array Materials

Several materials were investigated as potential coatings to be used to raise the IR emittance of both sides of the cell. Tefzel and Teflon were considered for coatings on the front (cell) side, while 200 Angstroms of Silicon or Germanium were considered for the backside surface. For the backside, an additional approach was considered in which the stainless steel coating was replaced with an aluminum coating, which could be removed after cell fabrication to expose the underlying high-emittance polyimide material.

Measured emittances for the cell-side coatings were in the range of 0.65 to 0.69, as shown in Table 3. The backside materials all produced emittances approaching the desired value of 0.8, as shown in Table 4. Based on these measurements and manufacturing issues, a cell design consisting of a Tefzel front coating and a removable Vacuum Deposited Aluminum (VDA) backside coating was selected. These coatings should keep the cell maximum predicted temperature below 92°C slightly exceeding the desired limit of 90°C.

PMAD thermal design

Because the PMAD module has a fairly significant mass, its temperatures will be strongly influenced by *orbit-average* temperature of the sphere which surrounds it. The solar cell material, on the other hand, has almost no mass and will respond quickly to short term changes in the environment. Because of this, the hottest environment for the PMAD package will be the $\beta = 90°$ orbit, where the sphere will be in the sun at all times. The sphere, however, can get slightly hotter in the $\beta = 0°$ orbit when it passes over the sub-solar point and receives albedo loads in addition to the direct sun and earth emitted IR which it receives in the high beta angle orbits. Worst cold-case conditions for both the PMAD package and the sphere will occur for the $\beta = 0°$ orbit.

The first PMAD configuration to be analyzed placed the battery and electronics together in

Coating	Emittance
200 Angstrom Si on polyimide :	.74 on low-e substrate .81 on high-e substrate
200 Angstrom Ge on polyimide :	.74 on low-e substrate .81 on high-e substrate
200 Angstrom VDA on polyimide : After VDA coating removed :	.03 .73 on low-e substrate .82 on high-e substrate

Table 4 - Coatings to Raise Back-Side Emittance

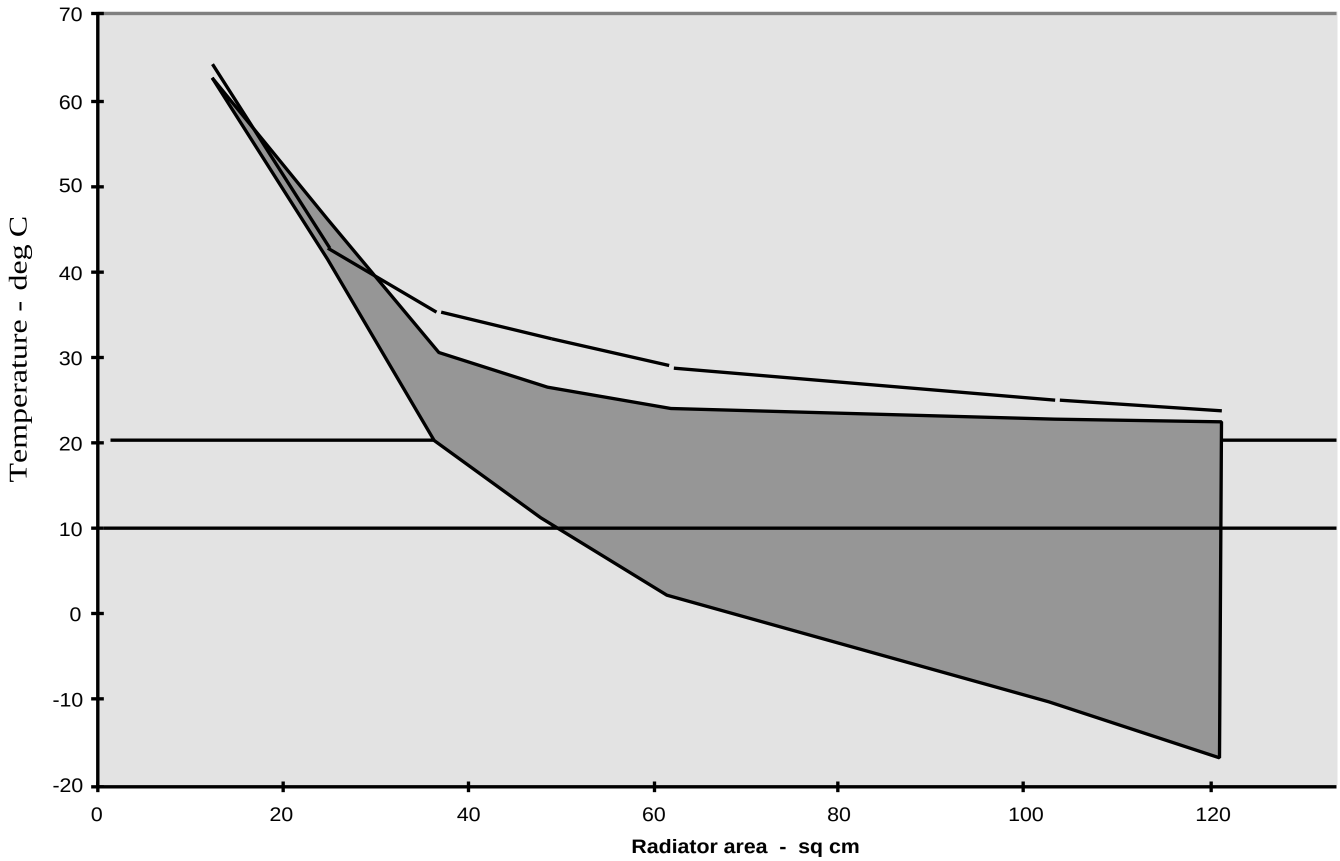

Figure 5 - PMAD Module Temperature

a small package at the center of the sphere. The electronics waste heat was simulated as a constant dissipation of 0.5 watts, while the battery was assumed to dissipate 0.5 watts during eclipse discharge and nothing during the sunlit portions of the orbit. Results of this analysis are shown in Figure 5 as predicted PMAD module temperature as a function of module radiating area. As can be seen in the figure, no reasonable amount of radiator area is sufficient to keep the battery below its 20°C upper prediction limit. If the upper limit for the battery could be raised to 35°C (25°C prediction limit), then 103 cm^2 of radiator area would work. In the $\beta = 0°$ cold case, however, the maximum radiator area one could have and still meet the lower allowable prediction limit of 10°C is 51 cm^2. It may be possible to effectively achieve this variation in radiator area by the use of emerging technologies such as micro-machined louvers or electrochromic surface finishes, which change emittance when an electrical potential is applied. Alternatively, it is estimated that 2 watts of heater power (0.5 watts maximum orbit-average power) would maintain the batteries above their lower limits with 103 cm^2 of radiator. As was stated earlier, however, the batteries could sometimes run as hot as 35°C with this design.

A second design configuration was explored to bring the maximum battery temperatures down to the desired level. In this configuration the battery and electronics are thermally isolated from one another and provided with separate radiators. This decouples the electronics waste heat from the battery and allows the electronics to run at higher temperature to dissipate their waste heat with a reasonable radiator area. Predicted temperatures for the battery and electronics in this configuration are shown in Figures 6 and 7, respectively. As can be seen in Figure 6, a radiating area of 36 cm^2 will keep the battery below its upper prediction limit of 20°C but that the radiator area can be no greater than 19 cm^2 if the minimum

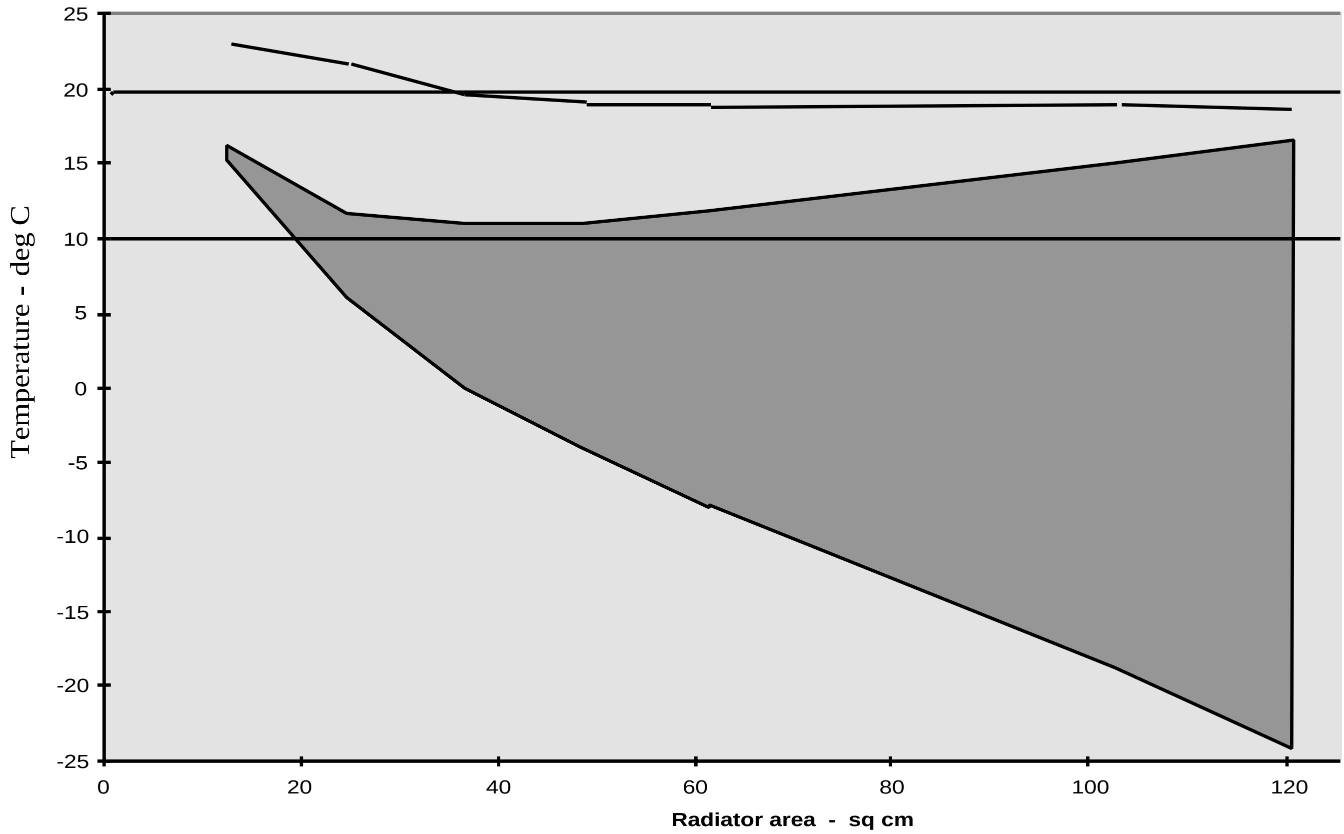

Figure 6 - Battery Module Temperature

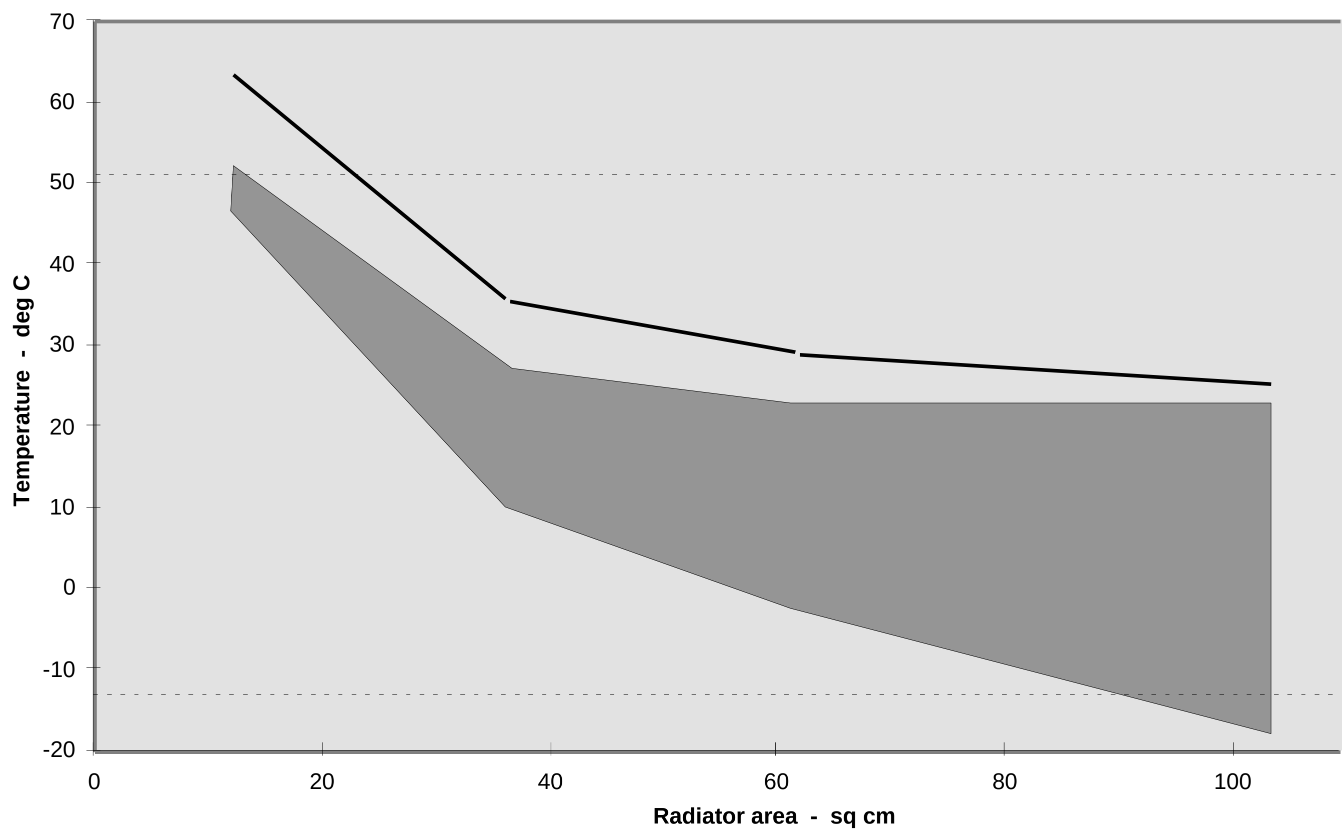

Figure 7 - Electronics Module Temperature

allowable prediction limit of 10°C is to be maintained. If the upper limit were raised slightly to 22°C then the 19 cm^2 radiator would satisfy both the hot and cold cases. This would result in flight battery temperatures in the 0 to 32°C range. Similarly, the power processing electronics will remain within allowable limits with as little as 23 cm^2 of radiator and no heater.

Summary / conclusion

The PowerSphere concept can provide adequate electric power for micro and nano satellites at a low cost and mass fraction. The thermal control aspects of the PowerSphere can be integrated into the materials from which the thin film solar arrays are fabricated. The thermal environment within the PowerSphere will provide the necessary thermal regulation for the battery and PMAD electronics without the addition of heaters or other active thermal control elements. The resulting integration of the thermal control aspects of the PowerSphere into the materials from which the PowerSphere is fabricated will result in a near optimal design with regards to a minimal mass for the electric power subsystem for micro and nano satellites.

Acknowledgment

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Reference

1. Simburger, Edward J., *"PowerSphere Concept"*, The Aerospace Corporation, Proceedings of Government Microcircuit Applications Conference, 8-11 March, 1999.